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DEFORMATION PATTERNS OF ANNULAR RINGS OF VARYING GEOMETRY SUBJECT TO STATIC AND DYNAMIC AXIAL COMPRESSION

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Abstract—Tests are described, in which mild steel rings of varying height/outside diameter/inside diameter ratios were subjected to axial compression, at different platen speeds and under different lubrication conditions. Deformed rings were sectioned and etched, to reveal the different deformation mechanisms effective. Photographs and photomacrographs showing typical results are presented, along with autographic records of the static operation.

INTRODUCTION

THE COMPRESSION of a short hollow cylinder between rigid parallel platens, i.e. the "ring" test, has been extensively examined as a means of determining the frictional conditions existing at the cylinder/platen interface. Depending upon the proportions of the ring, the central hole may increase or decrease with only slight changes in the frictional conditions, and thus affords a sensitive measure of the latter quantity. References 1 and 2 review work in this field.

An assumption common to analyses of the ring test [2–7] is that the strain at any radius is uniform over the whole height of the specimen, and it is usually accepted that with the cylinder proportions employed in most experimental investigations (where the ratio of the outside diameter to inside diameter to height could be say 6 : 3 : 2) this condition is satisfied. In the work of reference 1 however, where short mild steel rings were hot forged at high speed, (employing the ring test as a means of evaluating the effectiveness of different hot forging lubricants—the ring test is similarly employed for lubricants for cold extrusion in the work of reference 8), specimens deformed using "Copaslip"‡ were found to be unsymmetrical about a horizontal centre line. The reasons for this were considered as outside the scope of the paper and were not discussed, excepting that the occurrence was reported as being associated with low frictional conditions and high forging speeds, and partly attributed to lubricant deterioration and heat transfer between the billet and the lower die prior to forging.

The present authors are of the opinion however, that in addition to the aforementioned effects, unsymmetrical deformation may occur in the ring test—even under cold conditions and at low forging speeds—primarily as a result of this being the most favourable mode of deformation available to the workpiece, under the prevailing frictional conditions and workpiece geometry. The possibility of this is indicated by the theoretical analyses of Kudo [9] in which two modes of deformation available to a radially restrained annular

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‡ "Copaslip" is the trade name of an anti-seize compound consisting of finely divided metallic lead and micro-size particles of copper in a bentone grease [1].

ring, axially compressed under a range of frictional conditions, are considered. The first mode—the parallel velocity field—assumes that the strain-rate of the material element is independent of its vertical co-ordinate, i.e. the strain at any radius is uniform over the whole height of the specimen. The second mode—the triangular velocity field—assumes that the deforming region consists of two or three annular parts which appear triangular in cross-section, where the sides of the triangular sections are lines of velocity discontinuity. It is established [9] that for a solid cylinder compressed between rough platens, the triangular velocity field provides a lower mean platen pressure than the parallel velocity field over a range of cylinder height to diameter ratio of from approximately 0·3 to 1·1. Whilst the much more complex case of a radially unrestrained annular ring was not considered, it is possible that in this case also a triangular velocity field mode of deformation may be favourable, under particular frictional and geometric conditions.

The presently reported tests were initiated, therefore, to attempt to establish the effective deformation mechanisms of mild steel cylinders of varying geometry, tested under different lubrication conditions and at different platen speeds.

MATERIAL, EQUIPMENT, PROCEDURE

Specimens

These were produced from cold rolled bright mild steel bar of $\frac{1}{2}$ in. diameter. Solid cylinders were used and also cylinders having central holes of diameter $\frac{1}{6}$, $\frac{1}{4}$ and $\frac{1}{3}$ in., such that ratios of inside diameter to outside diameter of 0, $\frac{1}{3}$, $\frac{1}{2}$ and $\frac{2}{3}$ were available. For each of these cross-sections, heights of $1\frac{1}{2}$, 1, $\frac{1}{2}$, $\frac{1}{4}$ and $\frac{1}{6}$ in. were employed, providing ratios of height to outside diameter of 3, 2, 1, $\frac{1}{2}$ and $\frac{1}{3}$. The geometry of the specimens is indicated in Table 1.

TABLE 1. SPECIMEN GEOMETRY
(Dimensions expressed as 1/24 inches)

	A				B				C				D			
	o.d.	i.d.	Wall thickness	Height	o.d.	i.d.	Wall thickness	Height	o.d.	i.d.	Wall thickness	Height	o.d.	i.d.	Wall thickness	Height
1	12	0	6	4	12	4	4	4	12	6	3	4	12	8	2	4
2	12	0	6	6	12	4	4	6	12	6	3	6	12	8	2	6
3	12	0	6	12	12	4	4	12	12	6	3	12	12	8	2	12
4	12	0	6	24	12	4	4	24	12	6	3	24	12	8	2	24
5	12	0	6	36	12	4	4	36	12	6	3	36	12	8	2	36

The specimens were turned approximately 0·010 in. oversize on length, after which they were copper plated to 0·001 in. over their entire surface. The plated specimens were then ground square and to length. During grinding, the copper plating was removed from the specimen ends; its presence on the walls of the specimen was to allow a visual assessment of the degree of inhomogeneous deformation, i.e. the "rolling up" of wall material onto the platens during compression. Platens were machined from tool steel, hardened to 50 Rockwell C, and then ground flat.

Three different frictional conditions were employed:

(i) *Dry*—The annular end areas of the specimens, and the platens, were roughened with 100 grade emery paper and then degreased with a solvent. Prior to each test, the platens were re-roughened.

(ii) *Initial lubrication*—The specimens and the platens were rubbed down through to 600 grade paper, diamond polished down to one micron grade, sprayed with P.T.F.E. from an aerosol can, and finally coated with a layer of graphite grease.

(iii) *Re-lubrication*—As for (ii) above, excepting that the operation was stopped for re-lubrication each time the current height of the specimen had been reduced by 10 per cent.

Equipment

Dynamic tests—Figure 1 shows the equipment used to carry out the dynamic tests. The mass of the tup can be varied by addition and/or removal of different sized weights—which are located and held by the central threaded shaft shown in Fig. 1—over the range of 10–90 lb. in increments of 5 lb. The available height through which the tup is free to fall is 14 ft. Impact velocities and energies of up to approximately 30 ft/sec and 1300 ft lbf may be employed therefore, and these two quantities—impact velocity and impact energy—varied independently of each other by only a simple and quick alteration of the tup mass.

Static tests—A Tinius Olsen 200×10^3 lbf capacity universal testing machine was employed for the static tests, an autographic record being taken in each case of force versus displacement.

Procedure

Dynamic tests—After measurement of its initial height, the specimen was lubricated as described above, and the platens similarly lubricated. The mass of the tup was altered so that it should provide the required impact energy at the chosen impact velocity. The tup was then winched to the appropriate height, the specimen placed on the lower platen, and the tup released by operation of the release cord. Measurement of the final height of the specimen enabled the engineering compressive strain, or fractional reduction, to be determined.

Static tests—These were carried out for specimens of all geometry, under each of the three different lubrication conditions, at a platen closing speed of about 25 thou/min. Where tests were interrupted to effect re-lubrication, the current height of the specimen was recorded as a check on the re-alignment of the autographic records; the latter are presented in the figures as smoothed curves without the periodic unloading and loading loops.

Metallurgical examination

After testing, specimens were sectioned across a diameter—for asymmetrically deformed specimens, a diameter of symmetry was chosen—mounted and polished, and then etched with 2 per cent Nital, to reveal regions of heavy deformation.

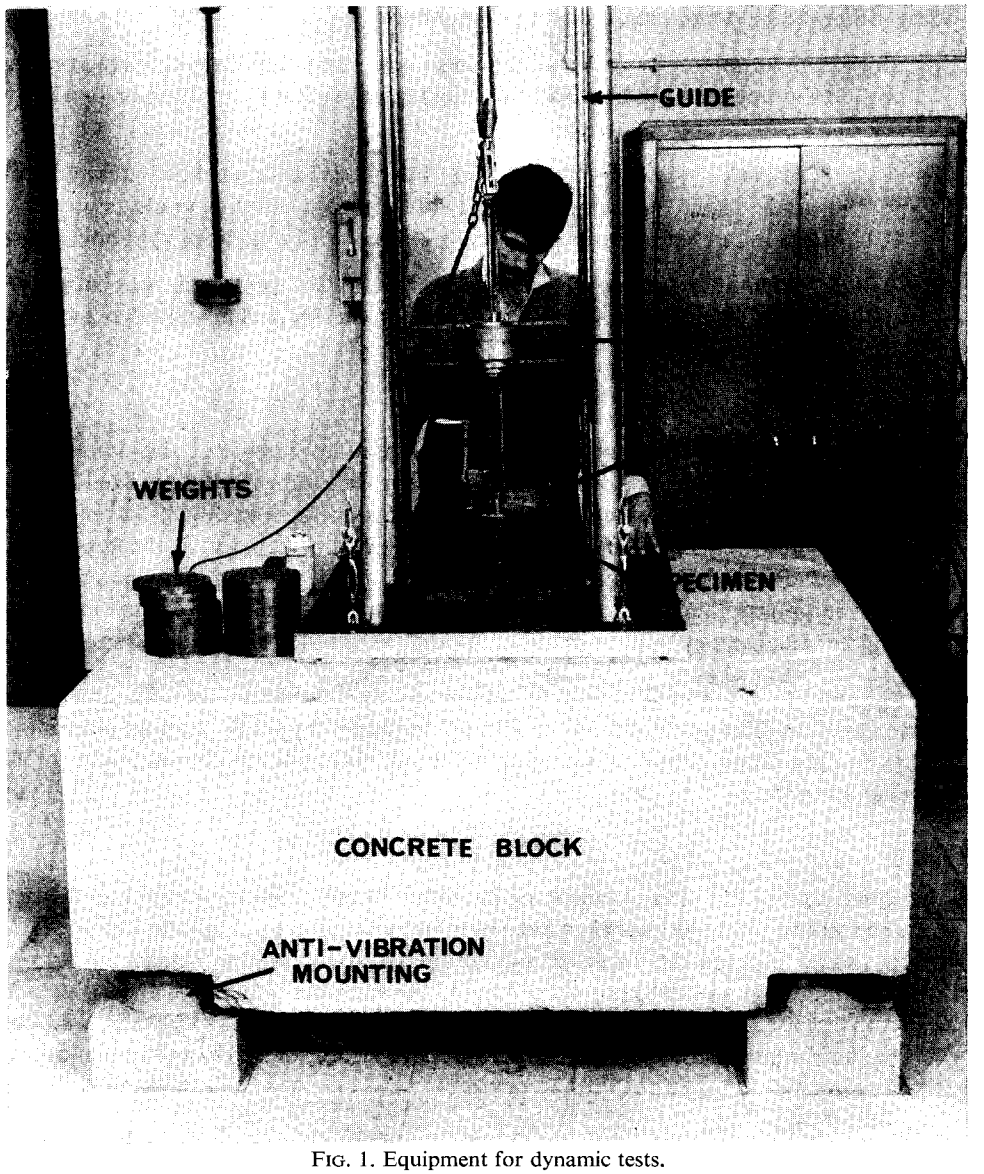


FIG. 1. Equipment for dynamic tests.

RESULTS

Coding

Specimens are identified throughout according to the following code:

Number—specimen height—1: $\frac{1}{6}$, 2: $\frac{1}{4}$, 3: $\frac{1}{2}$, 4: 1, 5: $1\frac{1}{2}$ inches.

Letter—specimen i.d.—A: 0, B: $\frac{1}{6}$, C: $\frac{1}{4}$, D: $\frac{1}{3}$ inches.

The proportions of the specimens are indicated in Table 1.

Figures 2(i), (ii) and (iii) are photographs of diametrically sectioned specimens, statically tested dry (top row), with initial lubrication (second row), and with re-lubrication (bottom

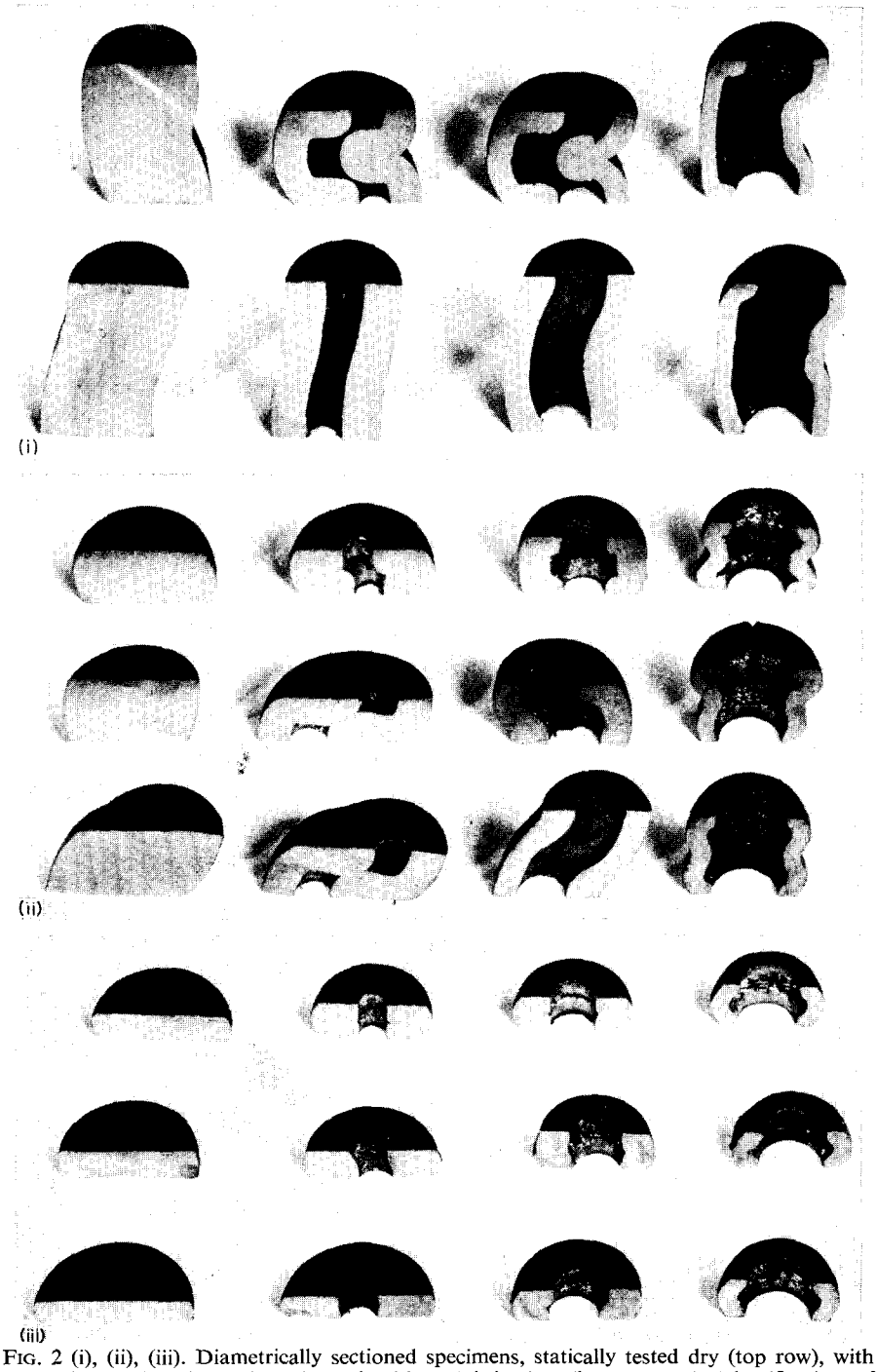


FIG. 2 (i), (ii), (iii). Diametrically sectioned specimens, statically tested dry (top row), with initial lubrication (second row), and with re-lubrication (bottom row). Identification of specimens according to code in "Results", where columns left to right refer to specimen type A to D respectively and (i), (ii) and (iii) refer to specimen type 5, 4 and 3 respectively.

row). Figure 3 presents typical results derived from the autographic records of the above static tests, where curves drawn full, chain dotted, and dotted, relate to dry, initial lubrication and re-lubrication conditions respectively.

Figures 4(i) and (ii) are photographs of diametrically sectioned specimens, dynamically tested dry (top row), and with initial lubrication (bottom row). Impact speeds of from 14 to 28 ft/sec, and tup masses of from 20 to 90 lb were used, as detailed in Table 2.

From examination of each specimen after sectioning and etching, an attempt was made to classify the different type of deformation effective, and this information is presented

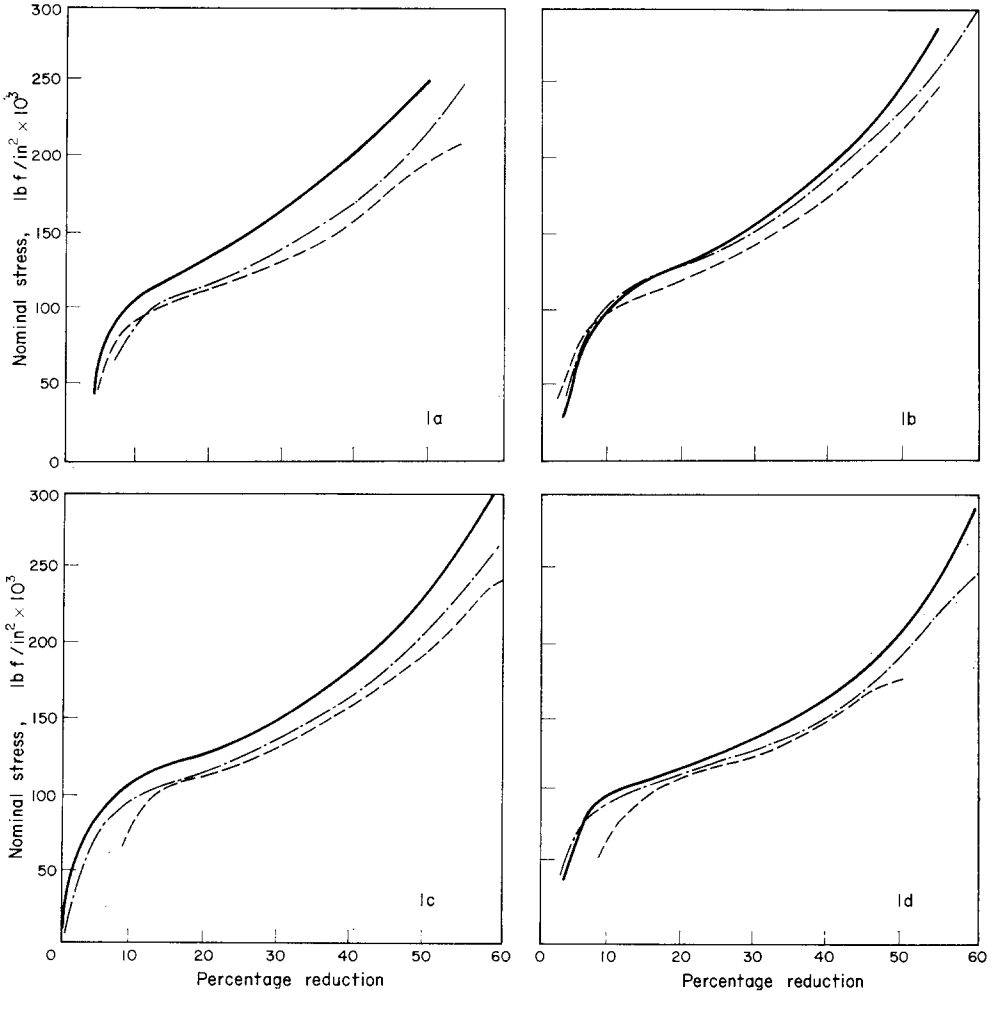
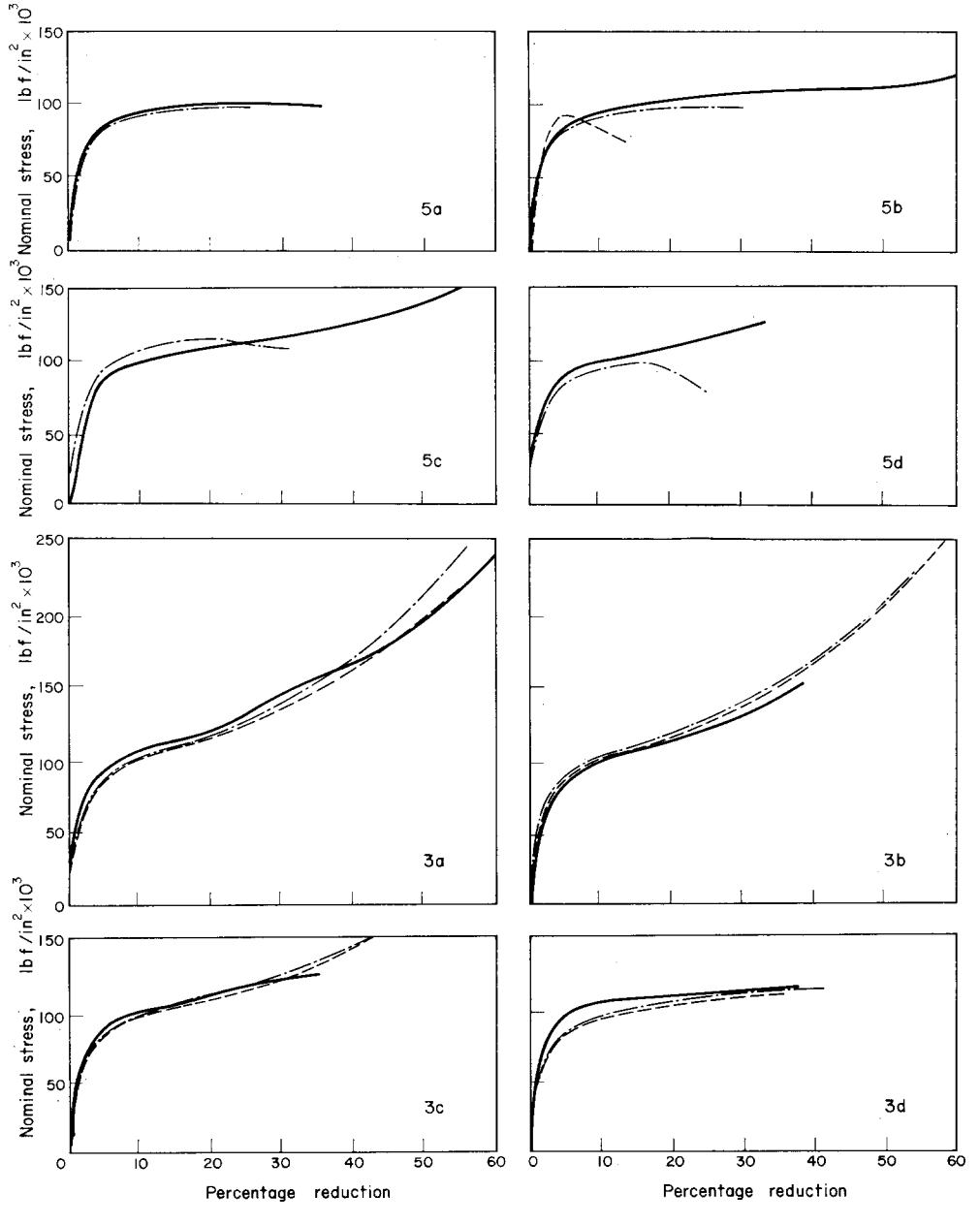


FIG. 3. Results derived from autographic records of static tests, where curves drawn full, chain dotted, and dotted, relate to dry, initial lubrication and re-lubrication conditions respectively. Identification of specimens according to code in "Results".

FIG. 3.—*Continued*



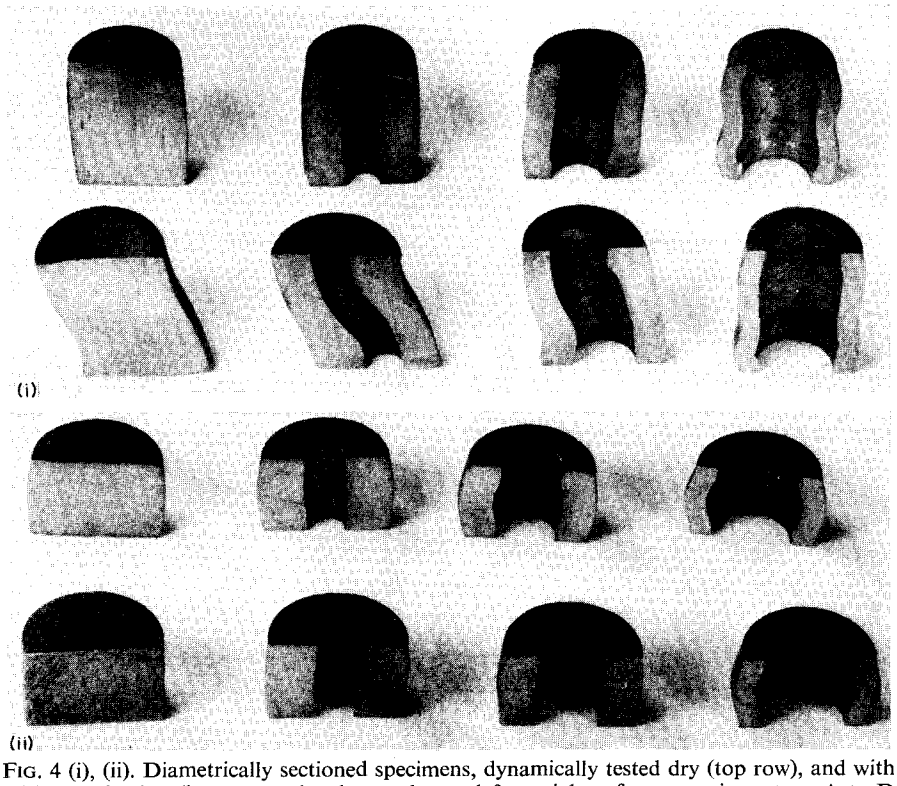


FIG. 4 (i), (ii). Diametrically sectioned specimens, dynamically tested dry (top row), and with initial lubrication (bottom row), where columns left to right refer to specimen type A to D respectively and (i) and (ii) refer to specimen type 4 and 3 respectively.

TABLE 2. DETAILS OF DYNAMIC TESTS

Specimen number	Specimen volume (in^3)	Tup mass (lb)	Tup drop height (ft)	Impact velocity (ft/sec)	Impact energy (ft-lb)	Energy/unit specimen volume ($ft\text{-}lb/in^3 \times 10^3$)	Percentage reduction	
							Dry tests	Initial lub. tests
1A	0·033	50	5·4	18·6	270	8·3	35	46
1B	0·032	45	5·4	18·6	240	7·6	35	49
1C	0·029	40	5·4	18·6	220	7·3	42	47
1D	0·018	30	5·4	18·6	160	8·9	50	49
2A	0·049	35	12	28	420	8·6	45	43
2B	0·048	30	12	28	360	7·5	39	44
2C	0·044	25	12	28	300	6·8	39	47
2D	0·027	20	12	28	240	8·7	45	49
3A	0·098	90	3	14	270	2·7	20	21
3B	0·096	80	3	14	240	2·5	20	21
3C	0·088	70	3	14	210	2·4	22	22
3D	0·055	50	3	14	150	2·7	22	22
4A	0·196	45	12	28	540	2·5	21	21
4B	0·192	40	12	28	480	2·5	22	25
4C	0·177	35	12	28	420	2·4	24	24
4D	0·109	25	12	28	300	2·7	23	22

in Tables 3 and 4. The code letters employed denote the following:

- G General, and almost uniform deformation over the whole of the specimen, expect for some barrelling, and no indication of regions of more intense local deformation.
- P_1 "Pressure cone", or "dead metal zone", i.e. an undeformed conical region at each end of the specimen, extending to both sides of the cross-section.
- P_2 Pressure cones, one at each side of the cross-section of the specimen.
- V Vertical asymmetry, the specimen being asymmetrical about a horizontal centre line.
- L Lateral asymmetry, the specimen being rotationally asymmetric.
- B Bucked specimen.

Figures 5(i), (ii) and (iii) are photomacrographs of specimens from static tests and illustrate types P_1, L and V respectively. Figures 6(i) to (viii) inc. are photomacrographs of specimens from dynamic tests, and types G and P_2 are represented by (v) and (viii) respectively.

A complete set of photographs and photomacrographs of all specimens tested is available in reference 10.

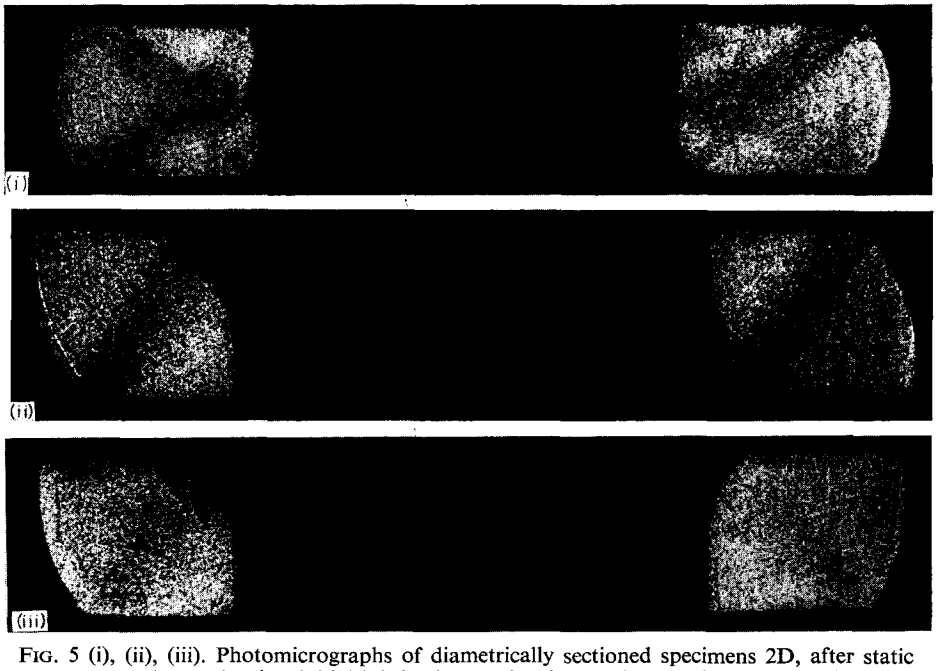


FIG. 5 (i), (ii), (iii). Photomicrographs of diametrically sectioned specimens 2D, after static testing under dry, initial lubrication, and re-lubrication conditions respectively.

DISCUSSION

Buckling failure

The analyses of Kunogi [3] predicts that thin-walled tubes will develop different buckled profiles according to their height to o.d. ratio, as illustrated in Fig. 7. From examination of the compressed specimens, it was observed that all specimens having height to o.d. ratios of less than one, deformed so that the outer walls developed a convex profile, i.e.

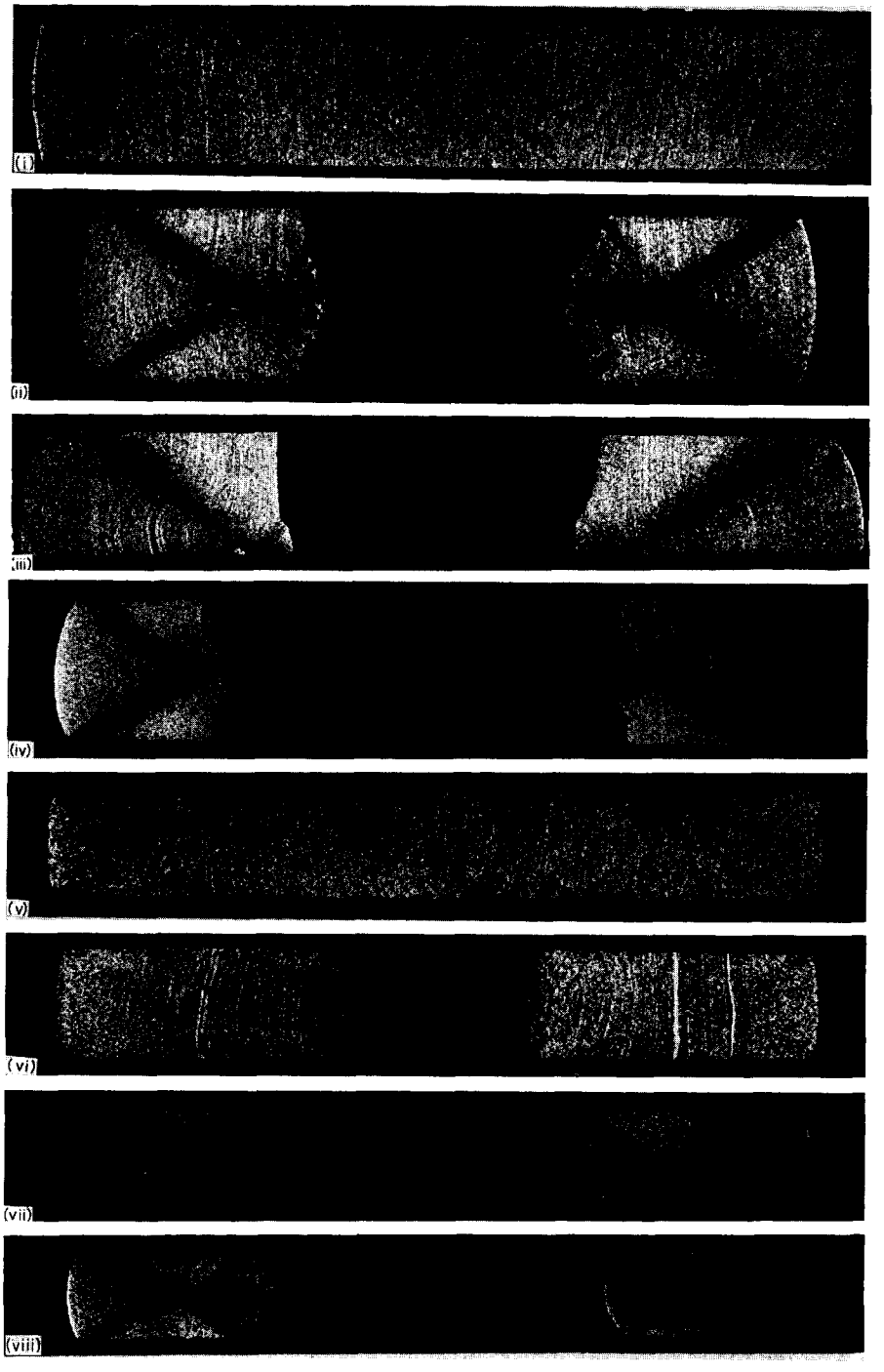


FIG. 6 (i)–(viii). Specimens 2A to 2D, and 1A to 1D inc. respectively, after dynamic testing under dry conditions.

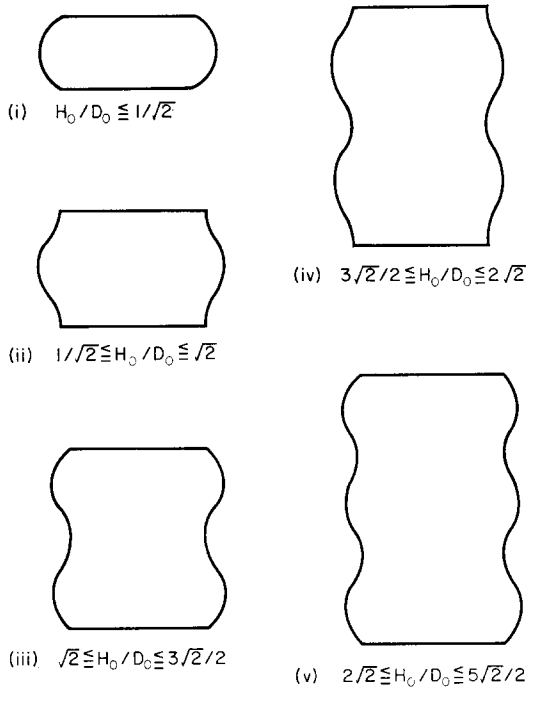

(i) $H_0/D_0 \leqq 1/\sqrt{2}$
(ii) $1/\sqrt{2} \leqq H_0/D_0 \leqq \sqrt{2}$
(iii) $\sqrt{2} \leqq H_0/D_0 \leqq 3\sqrt{2}/2$
(iv) $3\sqrt{2}/2 \leqq H_0/D_0 \leqq 2\sqrt{2}$
(v) $2\sqrt{2} \leqq H_0/D_0 \leqq 5\sqrt{2}/2$

FIG. 7. Profiles of buckled thin-walled tubes, after Kunogi [3], where H_o and D_o refer to the original height and o.d. respectively.

"barrelled", (or in some cases were almost straight), in accordance with Fig. 7(i); only photographs of those specimens having height to o.d. ratios of one and greater, and of interest therefore from the buckling aspect, are presented in the figures.

Static tests. For the specimens having the thinnest walls—$\frac{1}{12}$ in.—there is seen, from Fig. 2(iii)—height to o.d. ratio of one—to be agreement with the appropriate profile, Fig. 7(ii). Increasing wall thickness provides the normal "barrelled" profile. The degree of lubrication has no apparent effect on the buckling mode. For the specimens of Fig. 2(ii)—height to o.d. ratio of two—those having the thinnest walls are again buckled in agreement with the predictions of Kunogi, profile (iii) of Fig. 7.

There is no agreement for the specimens of Fig. 2(i) however; although there is extensive buckling, in each case the specimen has buckled asymmetrically. With the greater height to o.d. ratio of the specimens of Fig. 2(i) and the resultant increased susceptibility to lateral buckling as a strut, it is likely that the predicted axially—symmetric buckling mode will only occur at a much reduced wall thickness.

Dynamic tests. Although the deformation imposed in the dynamic tests was less than that imposed in the static tests, there is seen from examination of Fig. 4, to be no apparent difference in the respective buckling modes. For the height to o.d. ratios presented—one and two—the specimens having the thinnest walls show complete agreement with the predictions of Kunogi.

Deformation mechanism

Static tests. From examination of Table 3 it is noted that vertical asymmetry is associated with low friction—supporting the observation of Jain and Bramley [1]—and with shorter thin-walled specimens, where the wall thickness is of the order of twice the height. Lateral asymmetry however, whilst still associated with low friction, shows a tendency to occur with taller thick-walled specimens; such lateral asymmetry has been previously reported [11] for specimens of similar geometry tested under similar conditions of lubrication. Neither phenomena—excepting for one case of slight lateral asymmetry, specimen 4B—is experienced with specimens tested under dry conditions.

TABLE 3. DEFORMATION MECHANISM FOR STATIC TESTS

	Dry				Initial lubrication				Re-lubrication			
	A	B	C	D	A	B	C	D	A	B	C	D
1	G	G/P_2	P_2	P_2	G	G	G/P_2	G/V	G	G	G/V	V*
2	G	G/P_2	P_2	P_2/P_1	G	G/V	G/V	L	G	G/P_1	G/V	V
3	G/P_1	P_1	P_1	B/P_1	G	G/L	P_1	B/P_1	G	G	P_1/L	B/P_1
4	P_1	P_1/L	P_1	B	L	G/L	P_1/L	B	L	G/L	G/L	B
5	B	B	B	B	L	L	L/B	B	L	L	—	—

* Heavily pronounced line of "velocity discontinuity".

The occurrence of vertical asymmetry under static testing thus excludes the suggestion [1] that the phenomenon may be associated primarily with the relative transit time of plastic waves in comparison with the duration of deformation, or with the development of hydrodynamic lubrication. Jain and Bramley [1], by reference to the analyses of Lippmann [12] and Hillier [13] dismiss the effects of lateral inertia of the workpiece, and this is substantiated by the present static results.

Thinner-walled short specimens tested under dry conditions, were found to have developed separate pressure cones on each side of the cross-section, as shown in Fig. 6(viii). Tomlinson and Stringer [14] demonstrated in their work in the closing-up of artificially introduced cavities in cylindrical steel blocks compressed between rough platens, that the closing up of a central cavity occurs only when the pressure cones associated with the heavy friction between the platens and the block ends, intercept within the walls of the workpiece. For pressure cones having apex angles of 90°, interception would occur when the diametrical cross-section of the present specimens provides a height to wall thickness ratio of two. Further reduction would then result in the development of separate pressure cones on each side of the cross-section. Specimen 2D, presented as Fig. 5(i), of original height to wall thickness ratio of three, shows, after having suffered a reduction of about 50 per cent, the interference of the pressure cones and the commencement of radially inward flow of material. This feature is more evident in the dynamic dry test of this specimen, presented as Fig. 6(iv). Similar results are reported in reference 11.

Dynamic tests. From Table 4, it is seen that vertical asymmetry is associated, rather surprisingly, with only dry tests, specimens 1C and 2C. The latter specimen, presented as Fig. 6(iii), clearly shows the difference in the areas of the two ends. A visual examination of the specimen revealed a wide ring of copper—from the inner walls—on the inner edge of the lower end, and a smaller ring—from the outer walls—on the outer edge of the upper

TABLE 4. DEFORMATION MECHANISM FOR DYNAMIC TESTS

	Dry				Initial lubrication			
	A	B	C	D	A	B	C	D
1	G	G	G/V	P_2	G	G	G	G/P_2
2	G	P_1	V	P_2/P_1	G	G	G	L
3	G	G/P_1	G	B	G	G	G	B
4	G	G	B	B	L	L	L	B

end, consistent with shearing along the clearly defined dark etched lines resulting in wall material rolling onto the platens.

It will be noted that vertical asymmetry was not developed in the static dry test of the above specimen, 2C. It is well appreciated [15] that in operations carried out at high speed, such as, say, punching or blanking, the deformation zone is of much smaller width than that of the equivalent static operation, and in reference 16, factors leading to the reduced width are discussed. In the hot forging of steel billets, Slater [17] has shown that the concentration of deformation in linear regions can result in their becoming visibly hotter than the surrounding material, i.e. "heat lines", and at the present time [18] is investigating the metallurgical changes which can occur in cold dynamic forging under the effects of the high local temperatures—and subsequent rapid cooling by the adjacent comparatively cold material—generated in this manner. A feature associated with such locally increased temperatures is a locally reduced flow stress and a reduction therefore in the forming forces (Davies and Dhawan [19] have shown that the development of "thermo-plastic instability" [20] in high speed punching can lead to the required punch force falling effectively to zero), so that a mechanism favourable to static tests may not be effective in the dynamic case.

Static stress-reduction curves

Buckling and lateral asymmetry are reflected in the curves of Fig. 3 specimens 5A to 5D, by a low rate of increase of stress, and in some cases by a falling off in stress, with increasing reduction in the height of the specimen. The yield stress is the same for each test, at approximately 85×10^3 lbf/in^2.

For specimens 3, height equal to o.d., there is little difference in the curves for the three different lubrication conditions. Curves for A and B are almost identical, but with reducing wall thickness, the tendency to buckling again is reflected by the increasingly flatter curves of C and D.

With specimens of height equal to half their o.d., and more so with specimens of height equal to quarter their o.d., 1 of Fig. 3, the effect of the different lubrication conditions employed in the tests is shown in the stress-reduction curves. As predicted by the analyses of Siebel [21] and others, the yield stress for the results of dry tests on thicker-walled specimens lies above that for the results of lubricated tests, and also above that of equivalent tests using longer specimens. With further reduction, the curve for dry tests rises steeply, at a faster rate than for the lubricated tests. The general similarity of curves for specimens 1A to 1D however, suggests that all tendency to lateral asymmetry is suppressed with specimens of this geometry, and this is supported by examination of the photomacrographs.

It will be noted that with the specimen having the geometric proportions most frequently

employed [1] in the ring test, and that suggested by Male and Cockcroft [22], specimen 1C, whilst there is no evidence of buckling or lateral asymmetry, there is present a pronounced vertical asymmetry in the static re-lubrication tests and also in the dynamic dry test.

Dynamic energy-reduction values

For specimens of height to o.d. ratio of 1 and 2, in tests where the tup impact kinetic energy per unit specimen volume was maintained constant, there is seen from Table 2 to be no significant difference in percentage reduction, irrespective of the height of the specimen, or the lubrication conditions.

The effect of specimen/platen lubrication on the reduction of the specimens only becomes evident with height to o.d. ratios of $\frac{1}{2}$ and $\frac{1}{3}$, where the buckling mode of deformation, as discussed earlier, tends to be suppressed.

CONCLUSIONS

The conclusions of the presently reported investigation may be summarized as follows:

(1) Annular rings under axial compression were observed to buckle as predicted by the analyses of Kunogi, irrespective of the conditions of lubrication between the specimen ends and the platens, for height to o.d. ratios of 2 and less, and for wall thickness to o.d. ratios of $\frac{1}{6}$.

(2) Specimens of height to o.d. ratio of 3, tested statically under dry conditions, buckled axially asymmetrically (both solid cylinders and annular rings of all wall thickness to o.d. ratios), and not as predicted by Kunogi for thin-walled tubes.

(3) A large number of specimens, particularly those with height to o.d. ratios of 2 or 3, were observed to fail by lateral displacement of one end of the specimen relative to the other, under the reduced lateral restraint imposed by the platens in the initial and re-lubrication tests. This occurred both with solid cylinders and with annular rings of wall thickness to o.d. ratios of $\frac{1}{3}$, $\frac{1}{4}$ and $\frac{1}{6}$.

(4) Vertical asymmetry was developed in the specimen having the geometry most frequently used for the ring test; this occurred in the static re-lubrication test and also in the dynamic dry test.

(5) Further to the observations of Jain and Bramley [1], vertical asymmetry can also occur under static conditions and under conditions of high platen/specimen friction, and is not, therefore, associated only with low frictional conditions and high forging speeds.

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